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A Simple Comptonization Model

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ABSTRACT

We present an empirical model of Comptonization for fitting the spectra of X-ray binaries. This model, SIMPL, has been developed as a package implemented in XSPEC. With only two free parameters, SIMPL is competitive as the simplest empirical model of Compton scattering. Unlike other empirical models, such as the standard power-law model, SIMPL incorporates the basic physics of Compton scattering of soft photons by energetic coronal electrons. Using a simulated spectrum, we demonstrate that SIMPL closely matches the behavior of physical Comptonization models which consider the effects of optical depth, coronal electron temperature, and geometry. We present fits to *RXTE* spectra of the black-hole transient H1743–322 and a *BeppoSAX* spectrum of LMC X–3 using both SIMPL and the standard power-law model. A comparison of the results shows that SIMPL gives equally good fits and a comparable spectral index, while eliminating the troublesome divergence of the standard power-law model at low energies. Importantly, SIMPL is completely flexible and can be used self-consistently with any seed spectrum of photons. We show that SIMPL – unlike the standard power law – teamed up with DISKBB (the standard model of disk accretion) gives results for the inner-disk radius that are unaffected by strong Comptonization, a result of great importance for the determination of black hole spin via the continuum-fitting method.

Subject headings: Astrophysical Data: Data Analysis and Techniques

1. Introduction

Spectra of X-ray binaries typically consist of a soft (often blackbody or bremsstrahlung) component and a higher-energy tail component of emission, which we refer to generically as a “power law” throughout this work. The origin of the power-law component in both neutron-star and black-hole systems is widely attributed to Compton up-scattering of soft photons by coronal electrons (White et al. 1995; Remillard & McClintock 2006, hereafter RM06). This component is present in the spectra of essentially all X-ray binaries, and it occurs for a wide range of physical conditions.

The tail emission is generally modeled by adding a simple power-law component to the spectrum, e.g., via the model POWERLAW in the widely used fitting package XSPEC (Arnaud 1996). A few of the many applications where power-law models are employed include: modeling the thermal continuum (Shafee et al. 2006) or the relativistically-broadened Fe K line (Miller et al. 2008) in order to obtain estimates of black-hole spin; modeling the surrounding environment of compact X-ray sources, such as a tenuous accretion-disk corona (White & Holt 1982) or a substantial corona that scatters photons up to MeV energies (Gierliński et al. 1999); and classifying patterns of distinct X-ray states, e.g., in black-hole binaries (RM06).

Because of the importance of the power-law component, several physical models have been developed to infer the conditions of the hot plasma that causes the Comptonization. Models of this variety that are available in XSPEC are COMPTT (Titarchuk 1994), EQPAIR (Coppi 1999), COMPTB (Farinelli et al. 2008), BMC (Titarchuk et al. 1997), COMPBB (Nishimura et al. 1986), THCOMP (Życki et al. 1999), COMPLS (Lamb & Sanford 1979), and COMPPS (Poutanen & Svensson 1996). It is essential to use such physical models when one is focused on understanding the physical conditions and structure of a scattering corona or other Comptonizing plasma.

Often, however, the physical conditions of the Comptonizing medium are poorly understood or are not of interest, and one is satisfied with an empirical model that seeks to match the data with no pretense that the model describes the physical system. The model POWERLAW is one such empirical model which has been extraordinarily widely used in modeling black-hole and neutron-star binaries (see text & references in White et al. 1995; Tanaka & Lewin 1995; Brenneman & Reynolds 2006; RM06) and AGN (e.g., Zdziarski et al. 2002; Brenneman & Reynolds 2006). However, POWERLAW introduces a serious flaw: at low energies it rises without limit. The divergence at low energies is unphysical, and it often significantly corrupts the parameters returned by the model component with which it is teamed (e.g., the widely used disk blackbody component DISKBB; §3).

An excellent alternative to the standard power-law model for describing Compton scattering is provided by a convolution model that is based on a Green’s function that was formulated decades ago (Shapiro, Lightman & Eardley 1976; Rybicki & Lightman 1979; Sunyaev & Titarchuk 1980; Titarchuk 1994). In this approach the power-law is generated self-consistently via Compton up-scattering of a seed photon distribution; consequently, the power-law naturally truncates itself as the seed distribution falls off at low energies.

In this paper, we present our implementation of a flexible convolution model named SIMPL that can be used with any spectrum of seed photons. For a Planck distribution we show that SIMPL gives identical results to BMC, as expected since the two models are functionally equivalent (§2.3). Although SIMPL has only two free parameters, the same number as the standard POWERLAW, this empirical model is nevertheless able to very successfully fit data simulated using COMPTT, a prevalent physical model of Comptonization (§2.2).

We analyze data for two black hole binaries and illustrate the flexibility of SIMPL by convolving SIMPL with DISKBB, the workhorse accretion disk model that has been used for decades (Mitsuda et al. 1984). Our principal result is that SIMPL in tandem with DISKBB enables one to obtain fitted values for the inner-disk radius R_{in} for strongly-Comptonized data that are consistent with those obtained for weakly-Comptonized data (see §3.2). The standard power law, on the other hand, delivers very inconsistent values of R_{in} . As we show in §4.2, this result is consequential for the measurement of black hole spin via the continuum-fitting method: It implies that using SIMPL in place of the standard power law one can obtain reliable measurements of spin for a far wider body of data than previously thought possible, and for more sources (e.g., Cyg X-1).

In §2 we outline the model and in §3 we present a case study with several examples. We discuss the implications and intended applications of the model in §4 and conclude with a summary in §5.

2. The Model: SIMPL

The model SIMPL (SIMple Power Law) functions as a convolution that converts a fraction of input seed photons into a power law (see eq. [1]). The model is currently available in XSPEC¹. In addition to SIMPL-2, which is our implementation of the classical model described by Shapiro, Lightman & Eardley (1976) and Sunyaev & Titarchuk (1980), which corresponds to both up- and down-scattering of photons, we offer an alternative “bare-bones”

¹see <http://heasarc.nasa.gov/xanadu/xspec/manual/XSmodelSimpl.html>

implementation in which photons are only up-scattered in energy. The physical motivations behind the two versions of the model are described in §2.1, and the corresponding scattering kernels — the Green’s functions — are given in equation (2) and equation (3), respectively.

The parameters of SIMPL and the standard POWERLAW model are similar. Their principal parameter, the photon index Γ , is identical. However, in the case of SIMPL the normalization factor is the scattered fraction f_{SC} , rather than the photon flux. The goal of SIMPL is to characterize the effects of Comptonization as simply and generally as possible. In this spirit, all details of the Comptonizing medium, such as its geometry (slab vs. sphere) or physical characteristics (optical depth, temperature, thermal vs. non-thermal electrons), which would require additional parameters for their description, are omitted.

It is appropriate to employ SIMPL when the physical conditions of the Comptonizing medium are poorly understood or are not of interest. When the details of the Comptonizing medium are known, or are the main object of study, one should obviously use other models (e.g., COMPTT, COMPPS, THCOMP, etc.), which are designed specifically for such work. SIMPL, on the other hand, is meant for those situations in which a Compton power-law component is present in the spectral data and needs to be included in the model but is not the primary focus of interest. SIMPL should thus be viewed as a broad-brush model with the same utility as POWERLAW but designed specifically for situations involving Comptonization.

By virtue of being a convolution model, SIMPL mimics physical reprocessing by tying the power-law component directly to the energy distribution of the input photons. The most important feature of the model is that it produces a power-law tail at energies larger than the characteristic energy of the input photons, and that the power law does not extend to lower energies. This is precisely what one expects any Compton-scattering model to do and is a general feature of all the physical Comptonization models mentioned above. In contrast, the model POWERLAW simply adds to the spectrum a pure power-law component that reaches all the way downward to arbitrarily low energies. The difference between SIMPL and POWERLAW is thus most obvious at soft X-ray bands where SIMPL cuts off in a physically natural way whereas POWERLAW continues to rise without limit (e.g., see Yao et al. 2005).

Two assumptions underlie SIMPL. The first is that all soft photons have the same probability of being scattered (e.g., the Comptonizing electrons are distributed spatially uniformly). This is a reasonable assumption when one considers that, even in the best of circumstances, almost nothing is known about the basic geometry of the corona. For example, usually the corona is variously and crudely depicted as a sphere, a slab, or a lamp post. The second assumption is that the scattering itself is energy independent. This is again reasonable given the soft thermal spectra of the seed photons that are observed for black-hole and neutron-star accretion disks with typical temperatures of ~ 1 keV and a few

keV, respectively. For example, in the extreme case of a 180° back-scatter off a stationary electron, a 3 keV seed photon suffers only a 1% loss of energy, and even a 10 keV photon loses only 4% of its initial energy.

Figure 1 shows sample outputs from SIMPL when the input soft photons are modeled by the multi-temperature disk blackbody model DISKBB (Mitsuda et al. 1984). Results are shown for both SIMPL-2 and SIMPL-1, our alternative version of SIMPL that includes only up-scattering of photons; the spectra are shown for $\Gamma = 2.5$ and a range of values of f_{SC} . Note the power-law tails in the model spectra at energies above the peak of the soft thermal input and the absence of an equivalent power-law component at lower energies. This is the primary distinction between SIMPL and POWERLAW. SIMPL-2 and SIMPL-1 give similar spectra, but the spectrum from SIMPL-1 has a somewhat stronger power-law tail for the same value of f_{SC} . This is because SIMPL-1 transfers all the scattered photons to the high energy tail, whereas SIMPL-2 has double-sided scattering. Therefore, for the same value of f_{SC} , fewer photons are scattered into the high-energy tail with SIMPL-2. Correspondingly, when fitting the same data, SIMPL-2 returns a larger value of f_{SC} compared to SIMPL-1 (for examples, see §3 and Table 2).

2.1. Green’s Functions

Given an input distribution of photons $n_{\text{in}}(E_0)dE_0$ as a function of photon energy E_0 , SIMPL computes the output distribution $n_{\text{out}}(E)dE$ via the integral transform:

$$n_{\text{out}}(E)dE = (1 - f_{\text{SC}})n_{\text{in}}(E)dE + f_{\text{SC}} \left[\int_{E_{\text{min}}}^{E_{\text{max}}} n_{\text{in}}(E_0)G(E; E_0)dE_0 \right] dE. \quad (1)$$

A fraction $(1 - f_{\text{SC}})$ of the input photons remains unscattered (the first term on the right), and a fraction f_{SC} is scattered (the second term). Here, E_{min} and E_{max} are the minimum and maximum photon energies present in the input distribution, and $G(E; E_0)$ is the energy distribution of scattered photons for a δ -function input at energy E_0 , i.e., $G(E; E_0)$ is the Green’s function describing the scattering.

We now describe the specific prescriptions we use for SIMPL-2 and SIMPL-1. We also discuss the physical motivations behind these prescriptions, drawing heavily on the theory of Comptonization as described by Rybicki & Lightman (1979, hereafter RL79).

2.1.1. SIMPL-2

In sec. 7.7, RL79 discuss the case of unsaturated repeated scattering by nonrelativistic thermal electrons. Following Shapiro, Lightman & Eardley (1976), they solve the Kompaneets equation and show that Comptonization produces a power-law distribution of photon energies (eq. 7.76d in RL79). There are two solutions for the photon index Γ :

$$\begin{aligned}\Gamma_1 &= -\frac{1}{2} + \sqrt{\frac{9}{4} + \frac{4}{y}}, \\ \Gamma_2 &= -\frac{1}{2} - \sqrt{\frac{9}{4} + \frac{4}{y}},\end{aligned}$$

where the Compton y parameter is given by $y = (4kT_e/m_e c^2)\text{Max}(\tau_{\text{es}}, \tau_{\text{es}}^2)$. Up-scattered photons have a power-law energy distribution with photon index Γ_1 and down-scattered photons have a different power-law distribution with photon index Γ_2 .

We model this case of nonrelativistic electrons with the following Green’s function (Sunyaev & Titarchuk 1980; Titarchuk 1994; Ebisawa 1999), which corresponds to the model SIMPL-2:

$$G(E; E_0)dE = \frac{(\Gamma - 1)(\Gamma + 2)}{(1 + 2\Gamma)} \begin{cases} (E/E_0)^{-\Gamma} dE/E_0, & E \geq E_0 \\ (E/E_0)^{\Gamma+1} dE/E_0, & E < E_0. \end{cases} \quad (2)$$

The function is continuous at $E = E_0$, is normalized such that it conserves photons, and holds for all $\Gamma > 1$. Substituting (2) in (1) we see that SIMPL-2 has two parameters: f_{SC} and Γ . Although the model makes use of two power laws, their slopes are not independent.

As in the case of the standard power law, SIMPL includes no high energy cutoff. Technically, for any complete model of Comptonization, the up-scattered power-law distribution is cut off for photon energies larger than kT_e . To avoid increasing the complexity of our model, we have ignored this detail; extra parameters could easily be added to account for high energy attenuation if desired. By keeping the model very basic, SIMPL is a direct two-parameter replacement for the standard power law while bridging the divide between the latter model and physical Comptonization models.

2.1.2. SIMPL-1

The Green’s function (2) is obtained by solving the Kompaneets equation, which assumes that the change in energy of a photon in a single scattering is small. This assumption is not valid when the Comptonizing electrons are relativistic.

In sec. 7.3 of their text, RL79 discuss Compton scattering by relativistic electrons with a power-law distribution of energy: $n_e(E_e)dE_e \propto E_e^{-p}dE_e$. In the limit when the optical depth is low enough that we only need to consider single scattering, they show that the Comptonized spectral energy distribution (SED) is a power law of the form $P(E)dE \propto E^{-(p-1)/2}$. Equivalently, the photon energy distribution takes the form $n(E)dE \propto E^{-\Gamma}$, with a photon index $\Gamma = (p + 1)/2$. Hardly any photons are down-scattered in energy.

In sec. 7.5, RL79 show that repeated scatterings produce a power-law SED even when the relativistic electrons have a non-power-law distribution (see also Titarchuk & Lyubarskij 1995). In terms of the mean amplification of photon energy per scattering A and the optical depth to electron scattering τ_{es} , the Comptonized photon energy distribution takes the form $n(E)dE \propto E^{-\Gamma}$ with a photon index $\Gamma = 1 - \ln \tau_{\text{es}} / \ln A$. For the specific case of a thermal distribution of electrons with a relativistic temperature $kT_e \gg m_e c^2$, the amplification factor is given by $A = 16(kT_e/m_e c^2)^2$. Once again, hardly any photons are down-scattered.

For both cases discussed above, Comptonization is dominated by up-scattering and produces a nearly one-sided power-law distribution of photon energies. This motivates the following Green’s function, valid for $\Gamma > 1$, which we refer to as the model SIMPL-1:

$$G(E; E_0)dE = \begin{cases} (\Gamma - 1)(E/E_0)^{-\Gamma}dE/E_0, & E \geq E_0 \\ 0, & E < E_0. \end{cases} \quad (3)$$

The normalization factor $(\Gamma - 1)$ ensures that we conserve photons.

Although SIMPL-1 is most relevant for relativistic Comptonization, it can also be used as a stripped-down version of SIMPL-2 for non-relativistic coronae. The reason is that the low-energy power-law $(E/E_0)^{\Gamma+1}$ in equation (2) almost never has an important role. There is not much power in this component, and what little contribution it makes is indistinguishable from the input soft spectrum. Therefore, even for the case of nonrelativistic thermal Comptonization, for which the Green’s function (2) is designed, there would be little difference if one were to use SIMPL-1 instead of SIMPL-2.

2.2. Comparison to COMPTT

To illustrate the performance of SIMPL relative to other Comptonization models, we have simulated a 2×10^6 -count *BeppoSAX* (Boella et al. 1997) observation using the COMPTT model in XSPEC v12.4.0x.

For our source spectrum, we adopt disk geometry, a Wien distribution of seed photons at $kT_0 = 1$ keV, and a hydrogen column density of $N_{\text{H}} = 10^{21} \text{ cm}^{-2}$. We set the optical

depth and temperature of the Comptonizing medium to $\tau_c = 2$ and $kT_e = 40$ keV. Our simulation uses the LECS, MECS, and PDS detectors on *BeppoSAX*, which span a wide energy range $\sim 0.1 - 200$ keV (for details on the instruments, see §3). The total number of counts in the simulated spectra ($\sim 2 \times 10^6$) corresponds to a 3 ks observation of a 1 Crab source.

We analyze the simulated data with a model consisting of a blackbody (BB) coupled with SIMPL. We refer to this model as SIMPL \otimes BB (the \otimes is to emphasize that SIMPL represents a convolution). The best fits achieved have reduced chi-squared values of $\chi_\nu^2 = 1.00$ (SIMPL-1) and $\chi_\nu^2 = 1.06$ (SIMPL-2). The fitted BB temperatures are respectively 1.14 ± 0.02 keV and 1.29 ± 0.01 keV compared to 1 keV in the original COMPTT model. Figure 2 shows the fit using SIMPL-1 and Table 1 lists the best-fit parameters for both models.

In comparison, COMPBB, an alternative model of Compton scattering that assumes slab geometry, fits our simulated spectrum comparably well as SIMPL, with $\chi_\nu^2 = 1.05$ (Table 1). COMPBB returns the same temperature as SIMPL-2, $kT_{\text{bb}} = 1.29 \pm 0.01$ keV. Compared to the COMPTT progenitor, COMPBB gives similar estimates of the coronal temperature kT_e and optical depth τ_c (Table 1). Even though COMPBB is a physically more realistic model of coronal scattering than SIMPL, it does not outperform SIMPL in terms of fitting the COMPTT-generated data. Meanwhile, the model BB+POWERLAW performs quite poorly, yielding $\chi_\nu^2 > 2$. Parameters for this fit are given in Table 1. Note that the derived N_{H} using POWERLAW is much higher than either the original value or those from fits with SIMPL.

Though SIMPL is a purely empirical model, we see that it can deliver a remarkably successfully fit to data simulated using the physical model COMPTT. Even for a very cool corona with electron temperatures as low as $kT_e = 20$ keV, which causes COMPTT to produce noticeable curvature in the high-energy spectrum, we find that SIMPL-2 and SIMPL-1 achieve reasonable fits with $\chi_\nu^2 < 1.2$.

A significant virtue of SIMPL relative to the physical Comptonization models in XSPEC is that SIMPL can be employed in conjunction with any source of seed photons. The physical models, on the other hand, are typically restricted to treating only one or two predefined photon distributions. One standard choice of continuum model that is widely used in fitting Comptonized accretion disks is DISKBB+COMPTT. With SIMPL, one would instead employ the model SIMPL \otimes DISKBB. The latter not only generates the power law self-consistently via up-scattering of the seed photons, but it also has two fewer parameters.

2.3. Bulk Motion Comptonization

The model BMC describes the Comptonization of blackbody seed photons by a converging flow of isothermal gas that is freely falling toward a compact object, i.e., bulk motion Comptonization (see, e.g., Shrader & Titarchuk 1998; Titarchuk et al. 1997). BMC is an alternative to coronal Comptonization models and is structured *identically* to SIMPL-2 \otimes BB; both models are specified with just four parameters. As a direct demonstration in XSPEC that SIMPL-2 \otimes BB and BMC are identical, we analyzed our simulated *BeppoSAX* spectrum described above using both models. We found that the returned values of the column density N_{H} , the blackbody temperature kT , and the photon index Γ agreed in each case to four or more significant figures.

BMC has been variously used to support claims that Compton scattering off in-falling gas within several gravitational radii gives rise to the observed high energy power law in several black-hole binaries (e.g., Shrader & Titarchuk 1998, 1999; Borozdin et al. 1999). However, this is only one interpretation of the model; SIMPL-2 \otimes BB, and therefore BMC, can equally be used to support a more standard model of coronal scattering (operating with uniform efficiency at all energies, see §2 and §2.1.2). Thus, although BMC is designed specifically to model relativistic accretion inflows, its function is actually quite general.

One virtue of SIMPL relative to BMC is that SIMPL does depend upon discerning the nature of the Comptonizing region, be it corona, relativistic in-falling gas, or other. Another virtue of SIMPL is that it fully incorporates the utility of BMC while allowing complete flexibility in the choice of the spectrum of seed photons, e.g., SIMPL \otimes DISKBB is more appropriate for modeling Comptonization in accretion disks than BMC, which is hardwired to a Planck function.

The theory of bulk motion Comptonization is developed further and rigorously in Titarchuk et al. (1997). This paper describes a Green’s function that is more appropriate than the one used in BMC. A complete version of this Green’s function is incorporated into the more sophisticated model COMPTB. However, this model is again limited to treating scattering from a predefined set of (blackbody-like) seed photon distributions and includes additional free parameters. We find that the fitting results obtained using this Green’s function are intermediate between those given by SIMPL-1 and SIMPL-2 so long as the temperature of the in-flowing electrons, T_e , is above the observed energy range.

3. Data Analysis

In this section, we apply SIMPL to a sample of observations to illustrate how SIMPL compares with POWERLAW. To this end, we have selected two black-hole binaries, H1743–322 and LMC X–3. H1743–322 (hereafter H1743) is an especially pristine black-hole transient (see Remillard et al. 2006) since, for much of its 2003 outburst, its spectrum can be satisfactorily modeled with just absorbed ($N_{\text{H}} \approx 2.2 \times 10^{22} \text{cm}^{-2}$) thermal-disk and power-law components (McClintock et al. 2007b, hereafter M07). In particular, the 122 days of contiguous spectral data on which we focus do not require any additional components to accommodate the reflection or absorption features that are often present in the spectra of black hole binaries.

The spectra of H1743 were acquired by the *Rossi X-ray Timing Explorer* (*RXTE*) PCU-2 module (Swank 1999), *RXTE*’s best-calibrated PCU detector, and were taken in “standard 2” format. All spectra have been background subtracted and have typical exposure times ~ 3000 s. The customary systematic error of 1% has been added to all energy channels. The resultant pulse-height spectra are analyzed from 2.8 – 25 keV using XSPEC v12.4.0x (see M07 for further details).

While *RXTE* provides good spectral coverage in hard X-rays ($\gtrsim 10$ keV), which is most important for constraining the power-law component, it is not sensitive at low energies (< 2.5 keV). Therefore, *RXTE* data are generally insensitive to N_{H} . To complement the *RXTE* observations presented here, we have selected a *BeppoSAX* observation of LMC X–3, a persistent and predominantly thermal black-hole source with a very low hydrogen column ($N_{\text{H}} \approx 4 \times 10^{20} \text{cm}^{-2}$; Page et al. 2003; Yao et al. 2005).

The *BeppoSAX* narrow-field instruments provide sensitive measurements spanning a wide range in energy, from tenths to hundreds of keV. The low-energy concentrator system (LECS) and the medium-energy concentrator system (MECS) probe soft fluxes, from $\sim 0.1 - 4$ keV and $\sim 1.5 - 10$ keV, respectively. The phoswich detector system (PDS) is sensitive to hard X-rays from $\sim 15 - 200$ keV, and the high-pressure gas scintillation counter (HPGSPC) covers $\sim 4 - 100$ keV. In this analysis, we consider only the LECS, MECS, and PDS because the statistical quality of the HPGSPC data is relatively poor.

In reducing *BeppoSAX* data, we have followed the protocols given in the Cookbook for *BeppoSAX* NFI Spectral Analysis (Fiore et al. 1999). We use pipeline products and extract spectra from 8’ apertures centered on LMC X–3 for both the LECS and (combined) MECS detectors. For the PDS, which is a simple collimated phoswich detector, we selected the fixed rise-time spectrum. In our analysis, we have used standard response matrices and included blank-field background spectra with the appropriate scalings. No pile-up correction is necessary.

3.1. Steep Power Law State

About a third of the way through its nine-month outburst cycle, H1743 repeatedly displayed spectra in the steep power-law (SPL) state that were devoid of absorption features. A salient feature of the SPL state is the presence of a strong power-law component of emission. (For a review of black-hole spectral states and a precise definition of the SPL state, see Table 2 and text in RM06.) Twenty-eight such featureless spectra were consecutively observed over a period of about three weeks (spectra #58–85; M07). We focus here on one representative spectrum, #77. In Figure 3 we show our fits and the associated unabsorbed models obtained using DISKBB+POWERLAW and SIMPL \otimes DISKBB. Fitted spectral parameters are presented in Table 2.

The quality of fit (as measured by χ^2_ν) using either model is comparable. Nevertheless, there are distinct differences between the models. The fits with SIMPL have a $\sim 50\%$ larger disk normalization compared to POWERLAW and a $\sim 40\%$ lower N_H (Table 2). The fit using POWERLAW diverges at low energies, as revealed by removing photoabsorption from the fitted models (panels on the right in Fig. 3). The effect is quite severe and has no obvious physical explanation. In contrast, the fit using SIMPL is well behaved and the unabsorbed model is not divergent.

3.2. Thermal Dominant State

The key feature of the thermal dominant (TD) state is the presence of a totally dominant and soft ($kT \sim 1$ keV) blackbody-like component of emission that arises in the innermost region of the accretion disk. The TD state is defined by three criteria, the most relevant of which here is that the fraction of the total 2–20 keV unabsorbed flux in the thermal component is $\geq 75\%$. For the full definition of this state, see Table 2 in RM06.

Here we have chosen H1743 spectrum #91 which belongs to a sequence of ~ 50 featureless spectra (#86–136; M07) in the TD state. This spectrum has $\Gamma \sim 2$, which is somewhat harder than usual, but is otherwise typical of H1743’s TD state. Spectral fit results are shown in Figure 4. In addition, in order to further illustrate for the TD state the differences between SIMPL and POWERLAW at energies below the ≈ 2.5 keV response cutoff of *RXTE*, we use a *BeppoSAX* observation of LMC X–3; our results are illustrated in Figure 5. This observation was carried out on 1996 November 28 with exposure times of 1.8, 4.5, and 2 ks respectively for the LECS, MECS and PDS.

As in §3.1, we fit these data using DISKBB+POWERLAW and SIMPL \otimes DISKBB. The best-fit spectral parameters are listed in Table 2. Due to a calibration offset between the

various *BeppoSAX* instruments, we follow standard procedure and fit for the normalization of the LECS and PDS relative to the MECS, the best-calibrated of the three. We adopt the canonical limits of $0.7 - 1$ for LECS/MECS and $0.77 - 0.93$ for PDS/MECS. These normalizations are included in the tabulated results.

A comparison of the results obtained with POWERLAW and SIMPL confirms the trends highlighted in §3.1, namely the differences in normalization and N_{H} . However, they are more modest here because the Compton component is weaker in the TD state.

3.3. Comparison of SIMPL and POWERLAW

An examination of Table 2 reveals the following systematic differences in the derived spectral parameters returned when fitting with SIMPL vs. POWERLAW: SIMPL yields (i) a stronger and softer thermal disk component, i.e., a larger normalization and lower kT_* ; (ii) a generally steeper power law component (larger Γ); and (iii) a systematically lower N_{H} . As we now show, all of these effects can be simply understood.

Because POWERLAW produces higher fluxes than SIMPL at low energies, it tends to suppress the flux available to the (soft) thermal component, namely DISKBB in the examples given here. This explains why POWERLAW tends to harden the DISKBB component and to steal flux from it (i.e., reduce its normalization constant). Meanwhile, at low energies the POWERLAW component predicts artificially high fluxes that, in order to conform to the observed spectrum, depress the value of Γ . These differences between SIMPL and POWERLAW are most pronounced when the power law is relatively steep, i.e., typically when $\Gamma \gtrsim 3$.

Modest and reasonable values of N_{H} are returned in fits using SIMPL, as well as COMPTT and other Comptonization models, because the Compton tail is produced by the up-scattering of seed photons and there is no power-law component at low energies. In contrast, POWERLAW continues to rise at low energies, which forces N_{H} to increase in order to allow the model to fit the observed spectrum. This systematic difference is apparent in our fit results for the H1743 spectra and is especially prominent in the case of the LMC X-3 spectrum for which N_{H} differs by a factor of two. For H1743, the discrepancy in N_{H} is much less for the TD spectrum than for the SPL spectrum because the SPL state has both a steeper and relatively stronger power-law component.

We turn now to consider the DISKBB normalization constant, which is proportional to R_{in}^2 , the square of the inner disk radius (see footnotes to Table 2). For the pair of H1743 spectra, we see that the disk normalization obtained with POWERLAW is $\approx 35\%$ smaller in the SPL state than in the TD state (Table 2), indicating that R_{in} is smaller for the SPL

state. With SIMPL, on the other hand, there is no significant change in the normalization, and hence both the SPL and TD states can be modeled with a disk that has the same inner radius. The radius is constant because SIMPL recovers the original (unscattered) flux emitted by the disk, which POWERLAW cannot do.

This crucial ability to unify the inner regions of the accretion disk in thermally active states exhibiting both high and low levels of Comptonization (i.e., TD and SPL states) paves the way for a full general relativistic analysis which can formally link R_{in} to black-hole spin (see discussion in §4.2). Kubota & Makishima (2004) similarly identified a constant radius for the black hole binary XTE J1550–564 between the TD and SPL states in an analysis using the model DISKBB + THCOMP. Because THCOMP is implemented as an additive (i.e., non-convolution) model, Kubota & Makishima had to employ an awkward and ad hoc procedure to obtain their result (see their Appendix). Their work improved upon a similar result obtained for black-hole GRO J1655–40 (Kubota et al. 2001). With SIMPL, the modeling is significantly easier.

4. Discussion

4.1. Black Hole X-ray States

A standard method of classifying X-ray states in black hole binaries involves spectral decomposition into two primary components – a multi-temperature blackbody disk, DISKBB, and a Compton power law, POWERLAW (RM06). This method is compromised by the use of the standard power law when the photon index is large ($\Gamma \gtrsim 3$). In this case, at low energies the flux from the power law can rival or exceed the thermal component and thereby pollute it. As discussed in §2, intrusion of the power-law component at low energies is fundamentally inconsistent with Compton scattering.

This difficulty in classifying states, which is caused by the use of POWERLAW, is remedied by the use of SIMPL because the latter model naturally truncates the power-law component at low energies. It is useful to consider the intrinsic differences between the two models and how they influence the classification of black-hole X-ray states. Using POWERLAW, the thermal disk and tandem power-law emission are modeled independently. On the other hand, under SIMPL all photons originate in the accretion disk. Some of these disk photons scatter into a power law en route from the disk to the observer. As described in §3.3, fits employing SIMPL imply stronger disk emission and weaker Compton emission than those using POWERLAW. As a result, state selection criteria would need to be modified for classification using SIMPL. This topic is beyond the scope of the present paper.

4.2. Application to the Measurement of Black Hole Spin

During the past few decades, the masses of 22 stellar black holes have been measured, 17 of which are found in transient black hole binaries (RM06). Recently, we have measured the spins of four of these stellar black holes (Shafee et al. 2006; McClintock et al. 2006; Liu et al. 2008) by fitting their continuum spectra to our fully relativistic model of an accretion disk KERRBB2 (Li et al. 2005; McClintock et al. 2006) plus the standard power-law component POWERLAW. In the continuum-fitting method, spin is measured by estimating the inner radius of the accretion disk R_{in} (Zhang et al. 1997). We identify R_{in} with the radius of the innermost stable circular orbit R_{ISCO} , which is predicted by general relativity.

To date, we have conservatively selected only TD data for analysis (§3.2). Meanwhile, the transient black hole binaries spend only a modest fraction of their outburst cycle in the TD state and are often found in the SPL or some intermediate state (see Figs. 4–9 in RM06). Since for each source we seek to obtain as many independent measurements of the spin parameter as possible, our sole reliance on TD data has been a significant limitation. Using SIMPL, the highly Comptonized SPL state is now able to provide estimates of spin, a matter to be discussed more fully in (J. Steiner et al. 2009, in preparation). Not only will this allow us to substantially increase the size of our data sample for many sources, it also will likely allow us to obtain spin measurements for sources such as Cygnus X-1 that never enter the TD state (McClintock & Remillard 2006).

Our reason for developing SIMPL was to improve our methods for analyzing TD-state data in order to determine more reliable values of black hole spin. That SIMPL now allows us to determine spins for SPL-state data was a serendipitous discovery and a major bonus. We were motivated to develop SIMPL because we have been hampered by the use of POWERLAW in two ways. First, in all of our work we have exclusively used TD spectral data (e.g., Shafee et al. 2006), which is maximally free of the uncertain effects of Comptonization. The selection of these data is problematic because, as indicated in §4.1 above, it can be affected in unknown ways when the spectral index of the Compton component is large.

Secondly, of greater concern is the potential adulteration in the TD state of the thermal component by the power-law component, which can have an uncertain and sizable effect on the fitted value of the black-hole spin parameter. In the case of a number of spectra with steep power-law components, we found that the fitted values of the spin parameter were affected by the contribution of the power law flux at energies below ~ 5 keV; e.g., see § 4.2 in McClintock et al. (2006). In order to mitigate this problem, we applied in turn two alternative models: COMPTT, and a standard power-law component curtailed by an exponential low-energy cutoff, EXPABS×POWERLAW. The former model was unsatisfactory because we were unable to fit for reasonable values of both the coronal temperature kT_e and

the optical depth τ_c . The latter model was likewise unsatisfactory because it requires the use of an arbitrary cutoff energy E_c .

We developed SIMPL in order to sidestep these difficulties and uncertainties. At low energies, the model truncates the power law in the same physical manner as COMPTT and other sophisticated Comptonization models. SIMPL self-consistently ties the emergent power-law flux to the seed photons in order to deliver the power-law component via coronal reprocessing. An application of SIMPL to the measurement of the spin of the black-hole primary in LMC X-1 is described in L. Gou et al. (2009).

5. Summary

We present a new prescription for treating Comptonization in X-ray binaries. While no new physics has been introduced by this model, its virtues lie in its simplicity and natural application to a wide range of neutron-star and black-hole X-ray spectra. SIMPL offers a generic and empirical approach to fitting Comptonized spectra using the minimum number of parameters possible (a normalization and a slope), and it is valid for a broad range of geometric configurations (e.g., uniform slab and spherical geometries). The scattering of a seed spectrum occurs via convolution, which self-consistently mimics physical reprocessing of photons from, e.g., an accretion disk. In addition to this physically motivated underpinning, SIMPL remains as unassuming as POWERLAW but without its troublesome divergence at low energies.

Our model is valid for all $\Gamma > 1$. We have shown that SIMPL is able to provide a good fit to a demanding simulated data set, which was generated with the widely-used Comptonization model COMPTT. Furthermore, we have demonstrated that SIMPL and POWERLAW give very comparable results when fitting spectral data in terms of quality-of-fit and spectral index (see Table 2). This quality of performance holds true not only for spectra with weak Compton tails (TD state) but also for spectra requiring a large Compton component (SPL state). In the latter case, the model based on SIMPL gives physically more reasonable results for the soft end of the spectrum (e.g., see §3.3).

Using SIMPL \otimes DISKBB it will be important to revisit the classification of black hole states (RM06) for two reasons. First, the selection of TD data will no longer be adversely affected by the presence of a steep power-law component. Secondly, this model will allow some degree of unification of the TD state and SPL state, the latter being a more strongly Comptonized version of the former. In determining black hole spin via the continuum-fitting method using KERRBB2, SIMPL is a significant advance on three fronts: It will (1) enable the selection of

data with a dominant thermal component that is not mucked up by the effects of a divergent power-law component; (2) allow reliable spin measurements to be obtained using strongly-Comptonized SPL data, thereby substantially increasing the data sample for a given source; and (3) likely make possible the determination of the spins of some black holes that do not enter the TD state (e.g., Cygnus X-1).

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A. XSPEC Implementation

SIMPL is presently implemented in XSPEC. This version includes three parameters (two that can be fitted), the power-law photon index (Γ), the scattered fraction (f_{SC}), and a switch to set up-scattering only (SIMPL-1: switch > 0) and double-sided scattering (SIMPL-2: switch ≤ 0). Since SIMPL redistributes input photons to higher (and lower) energies, for detectors with limited response matrices (at high or low energies), or poor resolution, the sampled energies should be extended or resampled within XSPEC to adequately cover the relevant range. For example, when treating the *RXTE* data in §3, which has no response defined below 1.5 keV, the command “energies 0.05 50 1000 log” was used to explicitly extend and compute the model over 1000 logarithmically spaced energy bins from 0.05 – 50 keV.

Using SIMPL can be problematic when Γ is large, especially if the power-law component is faint or the detector response extends only to ~ 10 keV (e.g., *Chandra*, *XMM* or *ASCA*). When the photon index becomes sufficiently large, a runaway process can occur in which Γ steepens and the scattered fraction becomes abnormally high (typically $\gtrsim 50\%$, inconsistent with a weak power law). This occurs because scattering redirects photons from essentially a δ -function into a new function with characteristic width set by Γ . If Γ reaches large values ($\gtrsim 5$), the scattering kernel will also act like a δ -function, and the convolved spectrum will be nearly identical to the seed spectrum.

In such circumstances, we recommend bracketing Γ . In practice, the power-law spectral indices of black-hole systems are found to lie in the range $1.4 \lesssim \Gamma \lesssim 4$ (Remillard & McClintock 2006). An upper limit of $\Gamma \sim 4 - 4.5$ is typically sufficient to prevent this runaway effect, and this constraint should be applied if it is deemed appropriate for the source in question.

We advise against applying SIMPL to sharp components such as spectral lines or reflection components. SIMPL broadens spectral lines, and for prominent higher energy emission features (such as Fe K α), SIMPL can saturate the power-law flux with scattering from the line itself. To prevent this from occurring, such components should be invoked outside the scope of SIMPL. For example, the XSPEC model declaration “model phabs \times (smedge \times simpl(kerrbb)+laor)” would satisfy this recommendation.

REFERENCES

- Arnaud, K. A. 1996, in ASP Conf. Series, Vol. 101, Astronomical Data Analysis Software and Systems V, ed. G. H. Jacoby & J. Barnes (San Francisco: ASP), 17
- Boella, G., Butler, R. C., Perola, G. C., Piro, L., Scarsi, L., & Bleeker, J. A. M. 1997, A&AS, 122, 299
- Borozdin, K., Revnivtsev, M., Trudolyubov, S., Shrader, C., & Titarchuk, L. 1999, ApJ, 517, 367
- Brenneman, L. W., & Reynolds, C. S. 2006, ApJ, 652, 1028
- Cowley, A. P., Crampton, D., Hutchings, J. B., Remillard, R., & Penfold, J. E. 1983, ApJ, 272, 118
- Coppi, P. S. 1999, High Energy Processes in Accreting Black Holes, ed. J. Poutanen & R. Svensson (San Francisco: ASP), 161, 375
- Ebisawa, K. 1999, in ASP Conf. Series, Vol. 161, High Energy Processes in Accreting Black Holes, ed. J. Poutanen & R. Svensson (San Francisco: ASP), 39
- Farinelli, R., Titarchuk, L., Paizis, A., & Frontera, F. 2008, ApJ, 680, 602
- Fiore, F., Guainazzi, M., & Grandi, P. 1999, Cookbook for BeppoSAX NFI Spectral Analysis, Bepposax SDC
- Gierliński, M., Zdziarski, A. A., Poutanen, J., Coppi, P. S., Ebisawa, K., & Johnson, W. N. 1999, MNRAS, 309, 496

- Gou, L., McClintock, J. E., Liu, J., Narayan, R., Steiner, J. F., Remillard, R. A., Orosz, J. A., & Davis, S. W. 2009, arXiv:0901.0920 [astro-ph]
- Kubota, A., Makishima, K., & Ebisawa, K. 2001, *ApJ*, 560, L147
- Kubota, A., & Makishima, K. 2004, *ApJ*, 601, 428
- Lamb, P. & Sanford, P. W. 1979, *MNRAS*, 188, 555
- Li, L.-X., Zimmerman, E. R., Narayan, R., & McClintock, J. E. 2005, *ApJS*, 157, 335
- Liu, J., McClintock, J. E., Narayan, R., Davis, S. W., & Orosz, J. A. 2008, *ApJ*, 679, L37
- McClintock, J. E., & Remillard, R. A. 2006, in *Compact Stellar X-ray Sources*, ed. W. Lewin & M. van der Klis (Cambridge: Cambridge Univ. Press), 157
- McClintock, J. E., Remillard, R. A., Rupen, M. P., Torres, M. A. P., Steeghs, D., Levine, A. M., & Orosz, J. A. 2007b, arXiv:0705.1034v1 [astro-ph]
- McClintock, J. E., Shafee, R., Narayan, R., Remillard, R. A., Davis, S. W., & Li, L.-X. 2006, *ApJ*, 652, 518
- Miller, J. M., Reynolds, C. S., Fabian, A. C., Cackett, E. M., Miniutti, G., Raymond, J., Steeghs, D., Reis, R., & Homan, J. 2008, *ApJ*, 679, L113
- Mitsuda, K., Inoue, H., Koyama, K., Makishima, K., Matsuoka, M., Ogawara, Y., Suzuki, K., Tanaka, Y., Shibazaki, N., & Hirano, T. 1984, *PASJ*, 36, 741
- Nishimura, J., Mitsuda, K., & Itoh, M. 1986, *PASJ*, 38, 819
- Orosz, J. A. 2003, in *IAU Symposium, Vol. 212, A Massive Star Odyssey: From Main Sequence to Supernova*, ed. K. van der Hucht, A. Herrero, & C. Esteban (San Francisco: ASP), 365
- Page, M. J., Soria, R., Wu, K., Mason, K. O., Cordova, F. A., & Friedhorsky, W. C. 2003, *MNRAS*, 345, 639
- Poutanen, J. & Svensson, R. 1996, *ApJ*, 470, 249
- Remillard, R. A. & McClintock, J. E. 2006, *ARA&A*, 44, 49
- Remillard, R. A., McClintock, J. E., Orosz, J. A., & Levine, A. M. 2006, *ApJ*, 637, 1002
- Rybicki, G. B. & Lightman, A. P. 1979, *Radiative processes in astrophysics* (New York, Wiley-Interscience)

- Shafee, R., McClintock, J. E., Narayan, R., Davis, S. W., Li, L.-X., & Remillard, R. A. 2006, *ApJ*, 636, L113
- Shapiro, S. L., Lightman, A. P., & Eardley, D. M. 1976, *ApJ*, 204, 187
- Shrader, C. & Titarchuk, L. 1998, *ApJ*, 499, L31
- Shrader, C. R. & Titarchuk, L. 1999, *ApJ*, 521, L121
- Swank, J. H. 1999, *Nuclear Physics B Proceedings Supplements*, 69, 12
- Sunyaev, R. A. & Titarchuk, L. G. 1980, *A&A*, 86, 121
- Tanaka, Y. & Lewin, W. H. G. 1995, in *X-ray Binaries*, ed. W. Lewin, J. van Paradijs, & E. van den Heuvel (Cambridge: Cambridge Univ. Press), 126
- Titarchuk, L. 1994, *ApJ*, 434, 570
- Titarchuk, L. & Lyubarskij, Y. 1995, *ApJ*, 450, 876
- Titarchuk, L., Mastichiadis, A., & Kylafis, N. D. 1997, *ApJ*, 487, 834
- White, N. E. & Holt, S. S. 1982, *ApJ*, 257, 318
- White, N. E., Nagase, F., & Parmar, A. N. 1995, in *X-ray Binaries*, ed. W. Lewin, J. van Paradijs, & E. van den Heuvel (Cambridge: Cambridge Univ. Press), 1
- Yao, Y., Wang, Q. D., & Nan Zhang, S. 2005, *MNRAS*, 362, 229
- Zdziarski, A. A., Leighly, K. M., Matsuoka, M., Cappi, M., & Mihara, T. 2002, *ApJ*, 573, 505
- Zhang, S. N., Cui, W., & Chen, W. 1997, *ApJ*, 482, L155
- Życki, P. T., Done, C., & Smith, D. A. 1999, *MNRAS*, 309, 561

Table 1. Results of Fitting a Simulated COMPTT Spectrum

MODEL	χ^2_ν/ν	N_{H} (10^{22}cm^{-2})	Γ	f_{SC}	Norm(PL) ^a	kT_0 (keV)	Norm ^b	kT_e (keV)	τ_c
COMPTT ^c	...	0.1	...	...	...	1.	0.001	40.	2.
SIMPL-1 \otimes BB	1.00/731	0.28 ± 0.01	1.41 ± 0.02	0.84 ± 0.01	...	1.142 ± 0.015	10.9 ± 0.4	...	...
SIMPL-2 \otimes BB	1.06/731	0.31 ± 0.01	1.37 ± 0.02	0.87 ± 0.01	...	1.292 ± 0.010	7.8 ± 0.3	...	...
COMPBB	1.05/731	0.31 ± 0.01	...	...	...	1.292 ± 0.010	19.7 ± 0.7	43.6 ± 2.2	2.21 ± 0.03
BB+POWERLAW	2.02/731	0.68 ± 0.01	1.00 ± 0.01	...	$(5.0 \pm 0.2) \times 10^{-3}$	1.700 ± 0.008	0.89 ± 0.02	...	...

^aPOWERLAW normalization given at 1 keV in photons $\text{s}^{-1}\text{cm}^{-2}\text{keV}^{-1}$.

^bBB and COMPBB normalization = $\left(\frac{R/\text{km}}{D/10\text{ kpc}}\right)^2$ for a blackbody of radius R at a distance D ; COMPTT normalization is undefined.

^cCOMPTT model set to disk geometry (geometry switch = 1).

Table 2. Spectral Fit Results

Source State	Mission Detector	MJD	χ^2_ν/ν	$\frac{L_{\text{disk}}^{\text{a}}}{L_{\text{Edd}}}$	PHABS	SIMPL			DISKBB		POWERLAW	
					N_{H} (10^{22}cm^{-2})	Ver. ^b	Γ	f_{SC}	kT_* (keV)	Norm ^c	Γ	Norm(PL) ^d
H1743 SPL	<i>RXTE</i> PCA	52797.6	0.64/44	0.19	1.94 ± 0.17	...	...	...	1.189 ± 0.011	568 ± 31	2.64 ± 0.02	9.92 ± 0.54
			0.64/44	0.26	1.16 ± 0.17	S1	2.65 ± 0.02	0.170 ± 0.004	1.157 ± 0.011	875 ± 49	...	...
			0.64/44	0.27	1.19 ± 0.17	S2	2.65 ± 0.02	0.224 ± 0.005	1.162 ± 0.011	878 ± 50	...	...
H1743 TD	<i>RXTE</i> PCA	52811.5	0.67/44	0.22	1.53 ± 0.15	...	...	...	1.106 ± 0.006	869 ± 33	1.98 ± 0.03	0.52 ± 0.05
			0.67/44	0.23	1.48 ± 0.15	S1	1.98 ± 0.03	0.030 ± 0.001	1.104 ± 0.006	909 ± 35	...	...
			0.67/44	0.23	1.48 ± 0.15	S2	1.98 ± 0.03	0.037 ± 0.001	1.105 ± 0.006	910 ± 35	...	...
LMC X-3 TD	<i>BeppoSAX</i> ^e LECS,MECS, PDS	50415.5	1.05/729	0.58	0.073 ± 0.008	...	...	...	1.279 ± 0.011	24.5 ± 0.8	2.19 ± 0.11	0.055 ± 0.010
			1.08/729	0.60	0.044 ± 0.003	S1	2.41 ± 0.45	0.062 ± 0.021	1.238 ± 0.013	30.4 ± 1.2	...	...
			1.08/729	0.59	0.044 ± 0.003	S2	2.46 ± 0.48	0.085 ± 0.033	1.239 ± 0.012	30.3 ± 1.1	...	...

^aBolometric (0.1 – 20 keV) luminosity of the disk component in Eddington units. For H1743, we adopt nominal values: $M = 10 M_{\odot}$, $D = 7.5$ kpc, and $i = 70^\circ$. The fiducial values used for LMC X-3 are $M = 7.5 M_{\odot}$ and $i = 67^\circ$ (Cowley et al. 1983; Orosz 2003). For fits using SIMPL, this quantity describes the seed spectral luminosity.

^bVersion of SIMPL being used, i.e., S1 for SIMPL-1 and S2 for SIMPL-2.

^cFor an accretion disk inclined by i to the line of sight, with inner radius R_{in} at distance D , $\text{Norm} = \left(\frac{R_{\text{in}}/\text{km}}{D/10 \text{ kpc}} \right)^2 \cos i$.

^dPOWERLAW normalization given at 1 keV in photons $\text{s}^{-1} \text{cm}^{-2} \text{keV}^{-1}$.

^eThe cross-normalizations for $C_{\text{LM}} \equiv \text{LECS/MECS}$ and $C_{\text{PM}} \equiv \text{PDS/MECS}$ are fitted from 0.7 – 1 and 0.77 – 0.93 respectively. $C_{\text{LM}} = 0.802 \pm 0.283, 0.814 \pm 0.008, 0.813 \pm 0.008$ for the fits with POWERLAW, SIMPL-1, and SIMPL-2. C_{PM} is pegged at 0.93 for the same fits.

Note. — All errors are presumed Gaussian and quoted at 1σ .

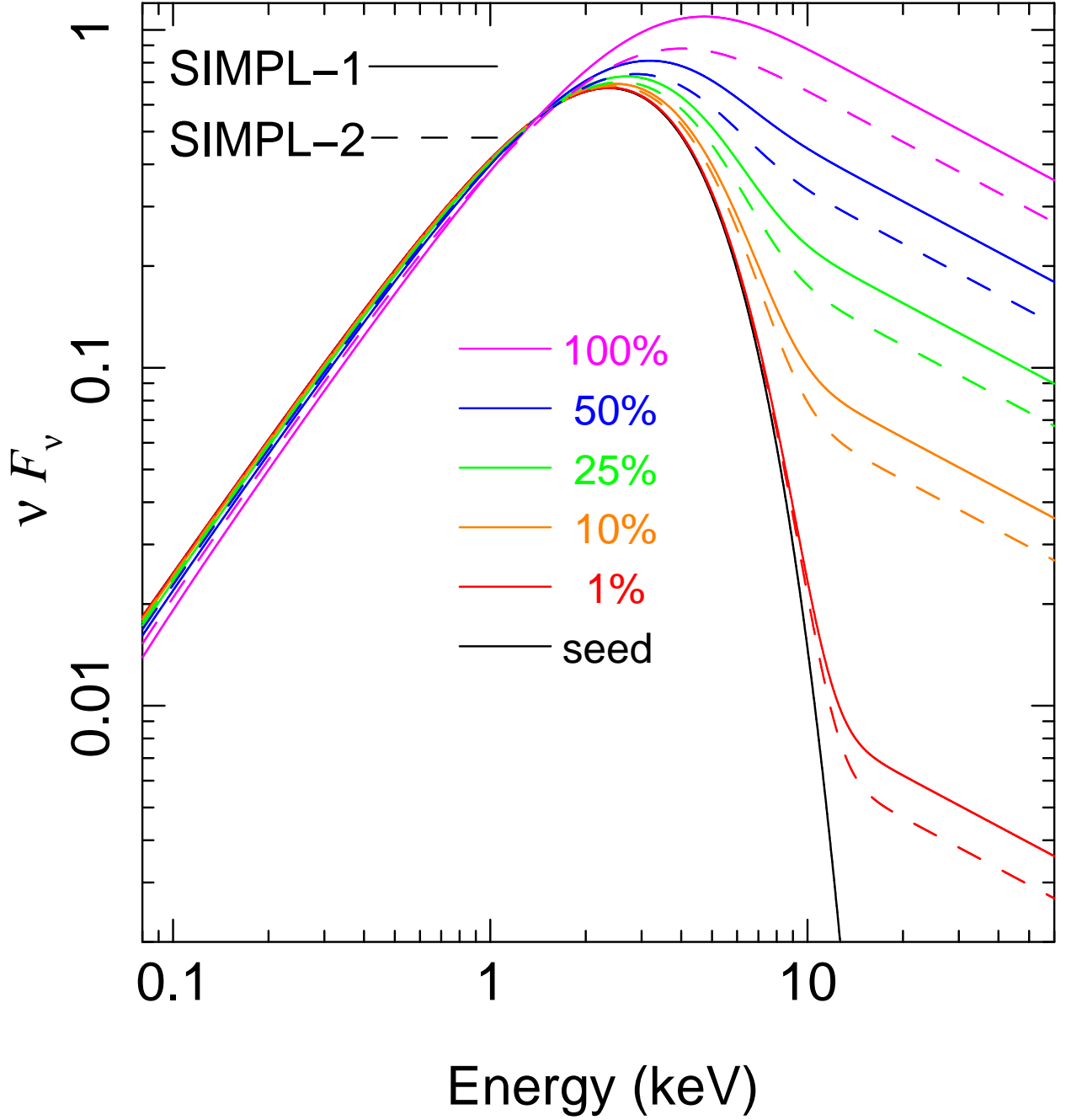


Fig. 1.— Spectral energy density vs. photon energy for a sample spectrum calculated with SIMPL-1 (solid lines) and SIMPL-2 (dashed lines). The models conserve photons and Comptonize a seed spectrum, which in the case shown is DISKBB with $kT_* = 1$ keV (black line). Ascending colored lines show increasing levels of scattering, from $f_{\text{SC}} = 1 - 100\%$.

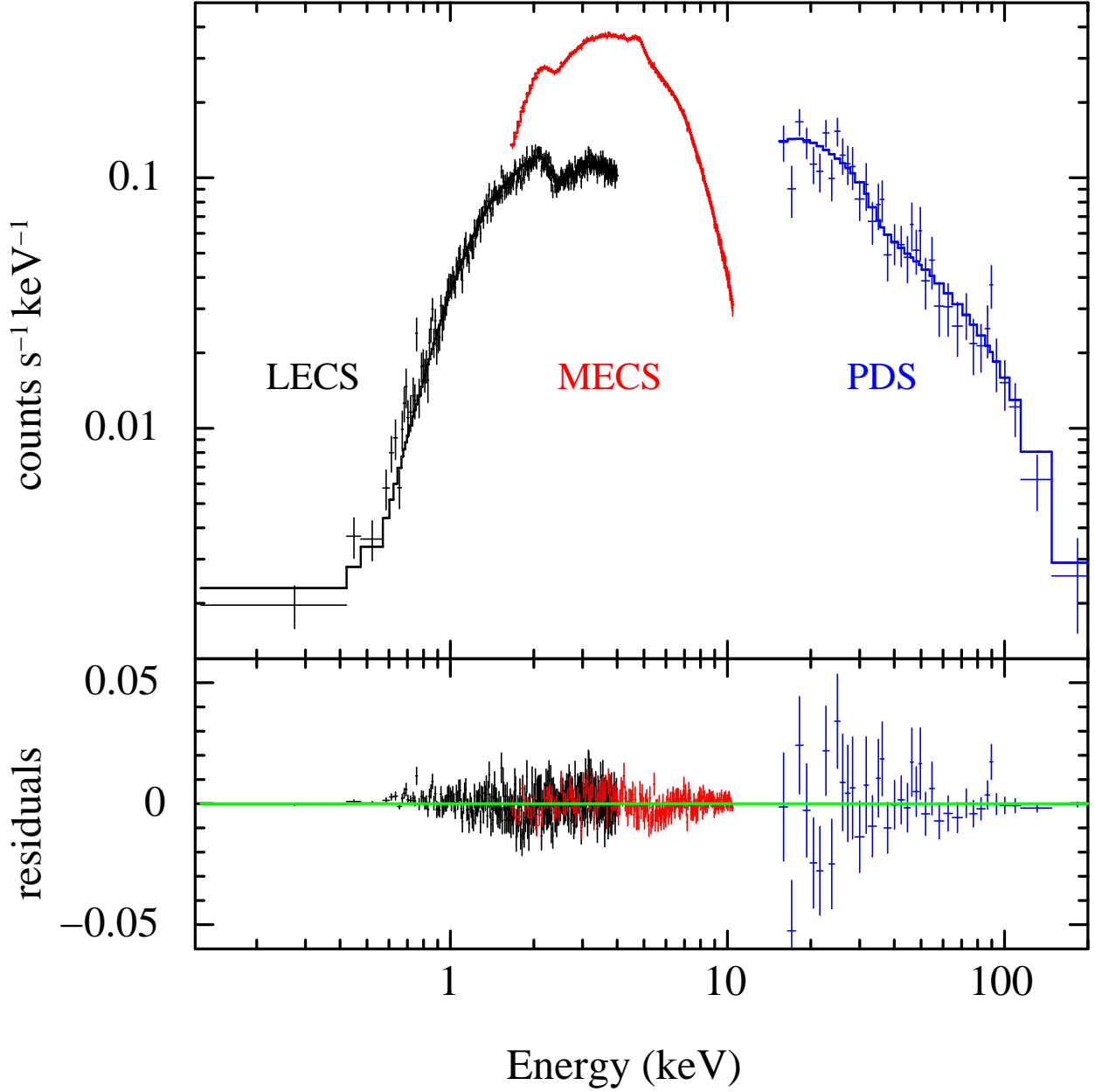


Fig. 2.— The data correspond to a simulated *BeppoSAX* observation with a total of 2.1×10^6 counts; the spectrum was generated using *COMPTT*. The histogram shows the fit achieved using *SIMPL-1*. This fit is performed over the recommended energy ranges of the narrow-field instruments (NFI), as given by the Cookbook for *BeppoSAX* NFI Spectral Analysis, yielding $\chi^2_\nu = 1.00$. For details, see Table 1. This example demonstrates the ability of *SIMPL* to match a representative spectrum generated by a physical model of Comptonization.

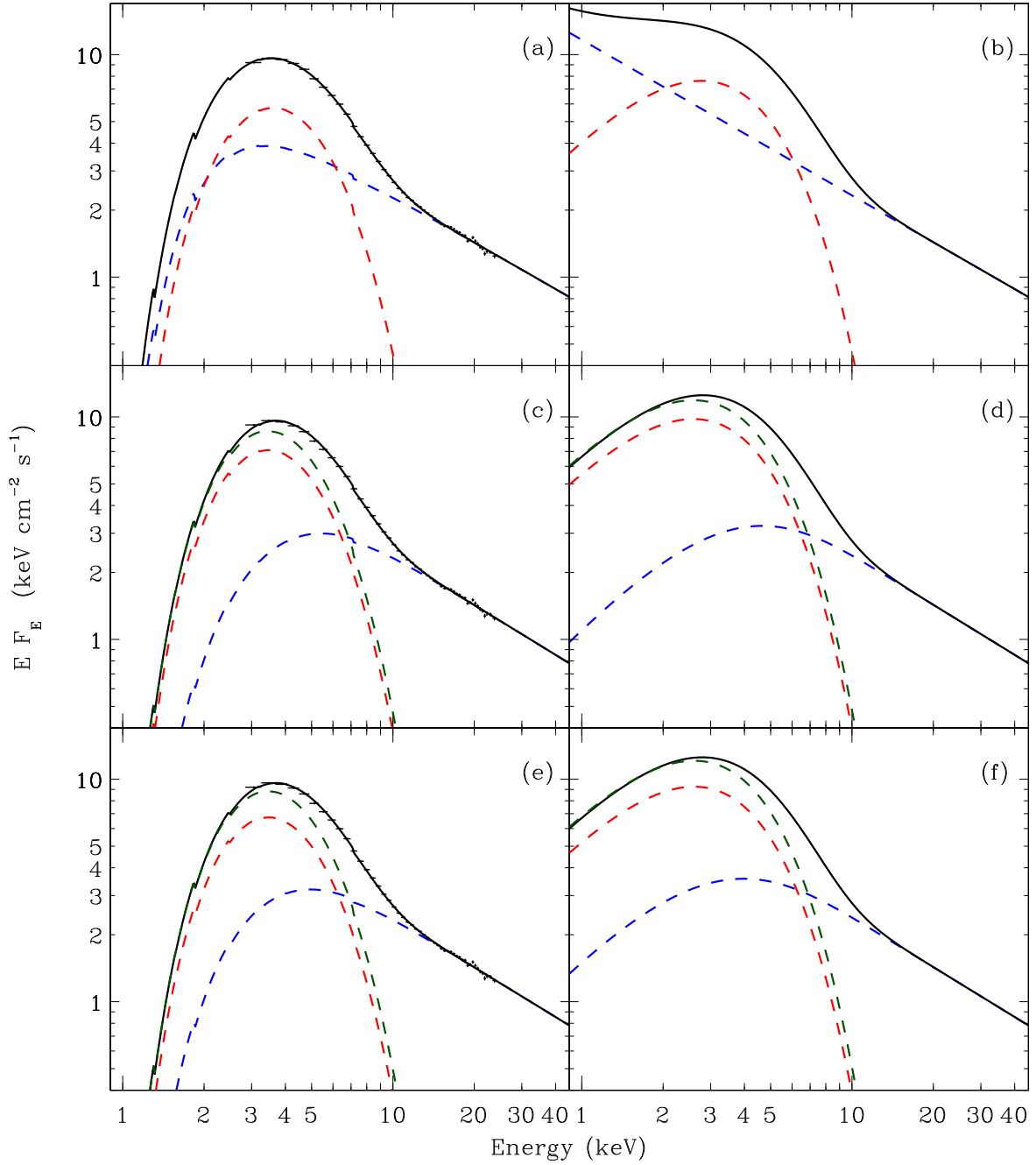


Fig. 3.— *left*: Unfolded spectral fits to an *RXTE* observation of H1743 in the SPL state and *right*: the corresponding unabsorbed models. Data are fitted using (a,b): $\text{PHABS} \times (\text{DISKBB} + \text{POWERLAW})$, (c,d): $\text{PHABS} \times (\text{SIMPL-1} \otimes \text{DISKBB})$, (e,f): $\text{PHABS} \times (\text{SIMPL-2} \otimes \text{DISKBB})$. The composite model is represented by a solid black line and the emergent disk and Compton components are shown as red and blue dashed lines respectively. The seed spectrum for SIMPL is shown (dashed) in green. Contrasting behaviors between SIMPL and POWERLAW are most clearly revealed in the unabsorbed models at low energies. Spectral parameters are given in Table 2.

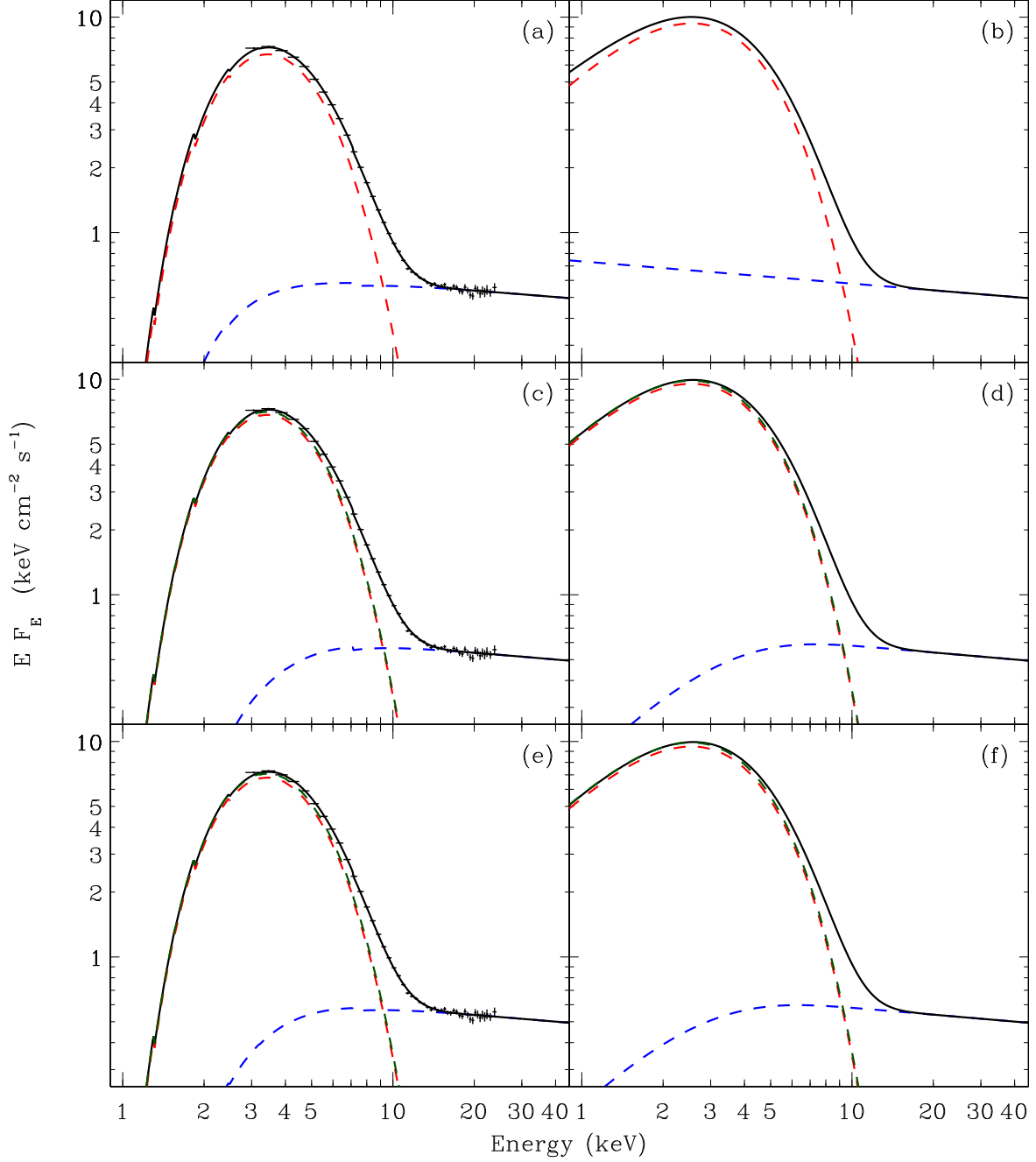


Fig. 4.— Same as Figure 3 except that the results shown here are for an *RXTE* observation of H1743 in the TD state. The systematic differences between the SIMPL and POWERLAW fits are greatly reduced compared to the differences shown for the SPL example in Figure 3.

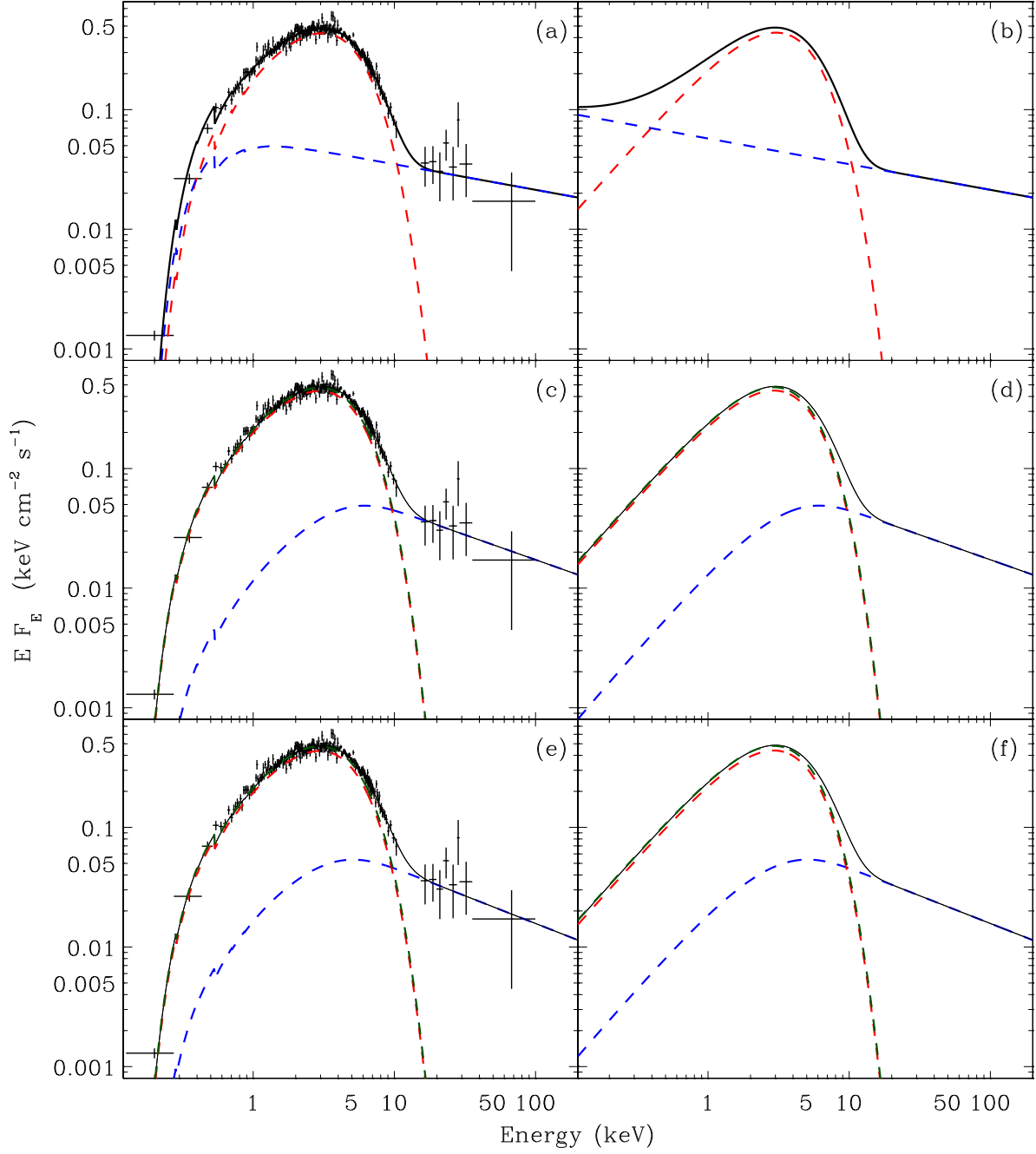


Fig. 5.— Same as Figures 3 and 4 for a TD *BeppoSAX* spectrum of LMC X-3. The data have been rebinned for plotting purposes only and both LECS and PDS counts have been rescaled by the fitted normalizations given in Table 2. At low energies (below ~ 0.5 keV), the unabsorbed model is strongly compromised for fits with POWERLAW